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"Brittle grain size reduction of feldspar, phase mixing and strain localization in granitoids at mid-crustal conditions (Pernambuco shear zone, NE Brazil)

Dear Editor,

We greatly acknowledge the reviews of the two Anonymous Referees. Their comments helped us clarify important parts of the paper and improve the quality of the manuscript. We also accepted all the technical corrections to text and figures. We are confident that the modifications and clarifications fully address all the remarks raised by the referees, and we are ready to submit a revised version of the manuscript. In the following outline we explain in blue how we addressed the reviewers' comments. We are looking forward to hearing your decision.

Yours sincerely,

Gustavo Viegas, Luca Menegon, Carlos Archanjo

<u>Referee #1</u>

1) Fluid content in the system, amount of H_2O and diffusivity of elements during deformation

The authors described that there is no hydration reactions of feldspar, suggesting dry condition during deformation. On the other hand, based on the observations such as (1) growth of new feldspar grains within intracrystalline fractures; (2) crystallographic preferred orientation (CPO) of plagioclase; (3) curved/undulose boundaries of K-feldspar grains; (4) precipitation of quartz in cavities; and (5) the pitted grain boundaries of feldspars, the authors argued a fluid phase was present on grain boundaries during deformation. This inference is reasonable, but I do not understand the authors have considered how much fluid content was present in the system; fluids were not sufficient to hydrate feldspars, but facilitated element diffusion along grain boundaries? I would like you to discuss the amount of H_2O and diffusivity of elements during deformation.

We agree that arguing for a dry system during amphibolite facies deformation in the Pernambuco shear zone is misleading. The main aspect that we want to highlight is that the shear zone does not show evidence of hydration reactions of feldspars, so that reaction weakening cannot be invoked as a mechanism of strain localization. The absence of feldspar-to-mica reactions does not necessarily indicate dry conditions, but rather P, T, fluids conditions at which feldspar is stable both as primary and as recrystallized grains (e.g. Goncalves et al., 2012).
We do not have exact constraints on the amount of H_2O in the system, since we did not measure LOI or intracrystalline water contents in nominally anhydrous minerals. In spite of this, we envisage a microstructural evolution that does imply the presence of fluids at grain boundaries as correctly pointed out by the referee. We speculate that the

required fluid could have been released from the interior of feldspar grains as a consequence of fracturing. Irrespective of the origin of fluid (primary vs infiltrated), we agree that the microstructural evolution that we suggest is not consistent with dry conditions and will clarify this aspect in the revised manuscript.

Specific Comments:

(1) P2963, L5–8: I do not see any preferential distribution of plagioclase in the inner parts of the bands and K-feldspar in the periphery of the bands in these figures.

We modified the text and emphasized that K-feldspar can be observed as coarse grains in the periphery of the band, while plagioclase grain size is homogeneously uniform across the band.

(2) P2963, L19–23: I do not identify which grain is quartz, and then cannot justify the microstructural characteristics. Please identify quartz grains in these figures.

We identified quartz in Fig. 6f and added Fig. 13 as additional example of fine quartz grains.

(3) P2964, L15–17: The data set of plagioclase chemistry is small, and more data are needed.

We agree that the data points for plagioclase are limited in number, and this is a limitation of the analytical technique when probing fine-grained (~ 3 μm) material. However, the presented data points are valid in the sense that the analyses were collected from individual feldspar grains and are not mixed. Even thought the dataset is small we prefer to keep it. Please note that in the original manuscript we admitted that such a limited dataset does not allow us to draw definitive conclusions on the potential role of chemical disequilibrium on recrystallization of feldspars.

(4) P2970, L4–17: The authors described the fine-grained feldspars filling the intracrystalline fractures are as "new grains" They are grains with overgrown new rims around old cores, and then they are not "new grains"!

This is semantic but it is good to try to clarify the terminology here. If new rims have grown around old cores, then the original small fragments (old cores) have experienced shape and size modifications so that technically they are new grains. We prefer to avoid the term "recrystallization" because we do not see evidence of recovery and dynamic recrystallization, but rather of nucleation and growth of new grains from fractured fragments (e.g. Stünitz, 1998; Trepmann et al., 2007; Menegon et al., 2013).

(5) P2971, L5-7: This interpretation is reasonable, but suppression of the secondary phases on the grain growth of quartz must be considered to evaluate the grain size of quartz.

We agree with the referee that the presence of second phases (i.e. the feldspathic matrix) could prevent quartz grain growth in the outer rims of the ribbons, where quartz grains share part of their boundaries with feldspar. However, please note that even within one-grain-thick monomineralic quartz ribbons embedded in a polyphase

matrix quartz grain growth is not necessarily suppressed and the individual grains grow in the direction of the ribbon length (e.g. high T striped gneiss or banded mylonites: Trouw et al., 2009) becoming markedly elongated. Grain growth in this case is suppressed only in the direction orthogonal to the ribbon width, but the grains can still grow parallel to the ribbon length.
To account for a possible second phase effect, we measured only quartz grains that were entirely in contact with other quartz grains and omitted the outer rim of grains in the ribbon. Thus, we are confident that the decrease in average grain size from the vein to the ribbon is not due to second-phase effect. We will include a representative grain boundary map in the revised manuscript.

(6) P2972, L14–24: The authors argued that the microstructures (i.e., curved/undulose boundaries of K-feldspar grains, precipitation of quartz in cavities, and the pitted grain boundaries of feldspars) are indicative of a presence of fluid on grain boundaries during deformation. This inference is reasonable, but I do not understand the authors have considered how much fluid content was in the system; fluids were not sufficient to hydrate feldspars, but facilitated element diffusion along grain boundaries? I would like you to discuss the amount of H2O and diffusivity of elements during deformation.

Please see reply to comment 1 above.

(7) P2974, L7–10: Please specify the values of parameters used to evaluate the relationship between differential stress and temperature. I would like to know whether they used the flow law for dry plagioclase aggregate or wet aggregate.

We have added a table containing the parameters used in the equations for quartz and plagioclase aggregates (see below). We used the flow law for wet plagioclase aggregates.

Table 2. Flow law parameters for quartz and feldspar used in this study

Flow Law	A (Mpa n^{-1} s^{-1})	m^{a}	Q(kJ mol^{-1})	n
Hirth et al (2001)	6.30957 x 10^{-12}	1	135	4
	log A (Mpa^{-n} μm^{m} s^{-1})	m		
Rybacki & Dresen (2004)	3.9±1.1	3	193±25	1

Technical corrections:

(1) P2969, L11: Alb91 should be Ab91.

Corrected.

(2) Figure 6: Please denote quartz grains in these BSE images.

Please see reply to Specific Comment (2).

(3) Figure 11: The misorientation profiles along A–A’ and B–B’ are for lines A–A’ and B–B’ in Figure 10, respectively? If so, please describe that in the captions of Figures 10 and 11. Furthermore, what is color code in Figure 10 for? If it represents misorientation of plagioclase (left) and K-feldspar (right), reference point should be indicated in each figure. What is arrow at color bar?

New caption of Fig. 10: (a) EBSD phase map of an intracrystalline fracture in feldspar porphyroclasts (red – quartz, blue – plagioclase, yellow – K-feldspar). Misorientation profiles A-A' and B-B' are shown in Figure 11; (b) optical micrograph of a fracture and its filling; (c) pole figures of feldspar as porphyroclasts and as recrystallized grains. See text for discussion.
The EBSD maps in Fig. 11 are "local misorientation maps". For a given pixel, the program calculates the degree of misorientation of that pixel with respect to the neighboring pixels in a radius of 3x3 pixels. We used a threshold of 3°, so that the maps only image the locations of misorientations that are less than 3°. The color scale shows how misoriented they are on a scale of 0 to 3º, and the arrow indicates the average misorientation (on a scale from 0 to 3º).

Referee #2

(1) The authors argue that the deformation occurred at "fluid-absent conditions" (page 2954, line 27) on the basis of the observation of missing metamorphic reactions of fractured feldspar. On the other hand they argue that after grain size reduction, diffusional creep of the polyphase feldspar matrix is the main deformation mechanism and quartz precipitated in cavities – which clearly would require the presence of a fluid phase. This contradiction needs to be discussed.

Please see reply to Referee's #1 main comment (1).

(2) The authors refer to a switch in deformation mechanism from brittle deformation to diffusional creep during the formation of shear bands. At the same time they discuss that stress and strain rate conditions are constant. Furthermore, on page 2976, line 1-7, the authors refer to seismic rupturing. How can this be compatible with constant stress and strain rate conditions?

We agree with the reviewer that the transition from fracturing to viscous flow clearly indicates oscillations in strain rates (and stress). Constant stress conditions were assumed for the viscous creep stage in order to compare and contrast the strain rate in the quartz veins deforming by dislocation creep with the ultrafine-grained feldspathic bands deforming by diffusion creep. Although brittle-viscous deformation cycles are probably common in nature, we do not see clear microstructural evidence of cyclic stress and strain rate variations in the sample. For example, recrystallized quartz grains in the vein are not overprinted by bulging, and the recrystallized vein microstructure is representative of a steady state flow. Subgrains have similar size as the recrystallized grains (see Fig. 12). Furthermore, there is no evidence of shear zone reactivation under different P-T-fluids conditions (e.g. biotite is stable and never even partially replaced by muscovite and chlorite, feldspar-to-mica reactions are absent). Our interpretation is that brittle grain size reduction of feldspar (at high bulk strain rates) triggered subsequent viscous strain localization in ultrafine-grained feldspathic bands primarily resulting from brittle grain size reduction. Evidence of any potential subsequent oscillations in stress and strain rate in the sample is absent. On page 2976, line 1-7, we speculate on the possible causes of the high bulk strain rates that resulted in extensive fracturing of feldspars.

(3) The topic of strain localization and differences in strain rates needs to be discussed more carefully and more specifically with respect to the specific microstructures.
The observations described are somehow contradictory: On the one hand it is stated on page 2971, line 1: “in contact to fractured and boudinaged feldspar porphyroclasts, quartz veins fill gaps, and is squeezed within fractures and boudin necks”. On the other hand they discuss that the quartz veins deform at lower strain rates, compared to the feldspar matrix.

We do not understand why these observations are contradictory. Quartz deforming by crystal plasticity is weaker than feldspar undergoing fracturing and boudinage, and tends to fill boudin necks and dilatant sites.

(4) The authors argue that quartz grain sizes in the matrix are smaller than in thin quartz ribbons, which are in turn smaller than those in larger veins. The grain sizes are used to infer the flow stresses, although following their argumentation, quartz dispersed in the matrix formed by precipitation – and not by dislocation creep with dynamic recrystallization, required to apply the recrystallized grain size paleopiezometer.

The referee is correct about the relevance of quartz grain size to paleopiezometric estimates. Indeed, we only used the recrystallized grain size of quartz from recrystallized monomineralic domains (vein and ribbon) and NOT from the dispersed grains in the feldspathic matrix (page 2974, line 16; page 2975, line 8; Fig. 8).

Furthermore, a discussion is needed whether the differences in grain sizes in the monomineralic quartz ribbons and veins may be due to later modification by grain growth: grain growth in the ribbons is hindered by the presence of phase boundaries at the contact to the matrix; the width of the ribbons is at least in parts restricted to the size of one quartz grain (Figure 13).

Please see the reply to Referee’s #1 Specific Comment (5).

Also, the authors need to take cutting effects into account, when they refer to “thin ribbons” and “veins”. By the way, where is the difference in thin ribbons and larger veins? Just the width? More specific descriptions and figures would help.

The main difference between “thin ribbons” and “veins” is that “thin ribbons” are always contained in the ultrafine-grained feldspathic matrix along localized C’ bands. Width is another important distinction, with “thin ribbons” never exceeding about 25 μm of width in thin section. We will clarify the key differences in the revised manuscript.

Specific Comments:

- Lines 5/6: “…≤15 μm in size)…”. Please specify: e.g. diameter or long axis?

  Diameter of the equivalent circle. Corrected in the abstract.

- Line 9: “…thin ribbons…” please specify, how thin?

Specified.

- Lines 13/14 "…from the transposed veins…" Which one? They are not introduced yet.

  Abstract modified accordingly.

- Line 16: "oriented growth…"of, please specify, what is the orientation?

- Lines 19/20: "assuming that the C' shear bands deformed under constant stress…"…difficult during fracturing and subsequent switch to diffusional creep.

  Text modified accordingly. Also, please see answer to comments 3 and 4 above.

- Line 21: please specify the observation/argumentation that would indicate why the strain rate would be one magnitude higher for the polyphase aggregate in contrast to monophase quartz ribbons?

  OK. The main argumentation is the result of the rheological modelling in Fig. 13, and this will be clarified in the text.

2. Geological setting and sample description

- What are the ambient P,T conditions and time constraints on magma emplacement

  OK, will draw from the literature.

- Page 2957, line 23 "EPSZ": what does this abbreviation mean?

  East Pernambuco Shear Zone, it will be clarified in the text.

- Page 2958, line 7: Give sample coordinates

  OK, will do.

- Page 2958, line 11: "high-temperature": please specify, what is the T?

  In this study the T has been estimated at 500-600°. This is consistent with the results of Neves et al. (1995, 1996, 2000).

- Page 2959, line 3: "high aspect ratio": please specify, how high?

  OK, will specify.

4.1.1. Domain 1: feldspar porphyroclasts

- Page 2961, lines 3, 4: "feldspar porphyroclasts have elliptical…shapes": please consider that porphyroclasts are 3D-objects!

- Page 2962, line 1: should it be: "Feldspar porphyroclasts are never, NOT even partially…:?

Text modified according to the referee's suggestions in both cases.

5. Discussion

- Page 2968, line 9: how was the pressure of 4.5-5 kbar inferred?

  Reference to Neves et al. (1996, 2000) will be added.

- Please consider, that temperature indicating the growth of metamorphic phases need not necessarily be the temperature of deformation.

- Page 2969, line 1-8: Please consider strain rate variations

  We agree with both comments.

5.3. Monomineralic quartz ribbons…

- Page 2971, line 1: "fractured and boudinaged feldspar porphyroclasts, quartz veins fill gaps, and is squeezed within fractures and boudin necks": this indicates that the quartz ribbons have a lower viscosity, i.e. deformed by a higher strain rate, compared to feldspar. The opposite is discussed a few sentences later..., however, from the text it does not get clear enough, which microstructures the authors refer to, when speaking of ribbons, veins and polyphase matrix..., the figures do not really help here!

  The statement in upper commas refers to recrystallized quartz in monomineralic veins, which has deformed at a higher strain rate than feldspar porphyroclasts, but slower than the feldspar matrix. Please see answer to comments 3 and 4 above. The three different microstructural and rheological domains of the samples are summarized in chapter 4.1 and figures 3-6 – we will further clarify the key differences in the revised manuscript.

- Page 2971, lines 1-10: Discussion that quartz dispersed in the matrix is smaller than in quartz ribbons, and grain size in thin quartz ribbons is smaller than in larger veins: a discussion is needed whether this may be due to later modification by grain growth: grain growth is hindered by the presence of adjacent phase boundaries. Here, the authors refer to Figure 8, where, however, the grain size is not really visible... AND quartz in matrix is formed by dissolution-precipitation processes, at least as discussed on the next page 2972, line 19-29, see comments below...

  We have addressed this aspect in previous replies and are happy to include grain boundary maps if the referee does not find Figure 8 sufficiently clear. Please note again that dispersed quartz in matrix was NOT used for palaeopiezometric calculations.

5.5. Strain localization in the ultrafine-grained polyphase matrix

- page 2974, lines 7-10: Rybacki and Dresen, 2004 mostly refer to anorthite-rich feldspar, however, here the anorthite component is relatively low. Please discuss a potential influence.

Available flow laws for plagioclase are mostly derived using anorthite and the effect of varying plagioclase composition has not been tested experimentally, at least to our knowledge. In the revised manuscript we will use both the Rybacki & Dresen (2000) flow law for anorthite and the Offerheim et al. (2001) flow law for albite to discuss potential influence of different anorthite content.

- page 2974, lines 11-20: I do not understand, how you can infer the flow stress of the shear band by the grain size of quartz dispersed in the matrix? The grain size paleopiezometer can only be applied for steady-state dislocation creep. On page 2972, line 19-29 it is stated the quartz dispersed in the matrix is precipitated in cavities. By the way, precipitated from which fluid?

  The referee is correct. But again, we did not infer flow stresses based on quartz dispersed in the matrix – to which we suggest formation via precipitation in cavities – but rather on the dynamically recrystallized monomineralic quartz ribbons contained in the feldspathic matrix. This is further clarified in comments 3 and 4 above and also in the revised version of the manuscript.

- page 2975, lines 5-12: I do not understand this part: the argumentation starts with quartz grain sizes in monomineralic ribbons and veins and inferred stresses from pa-leopiezometry (without referring to grain growth, see above). In which way do these results suggest that deformation is accommodated in the fine-grained matrix, which localizes strain via diffusional creep?

  We already addressed the potential issue of grain growth/second phase effect. Considering constant stress conditions across a tabular C' bands, we used the differential stress estimated from the quartz grain size in the ribbon to estimate the strain rate experienced by the feldspathic material deforming by diffusion creep, extrapolating an appropriate diffusion creep flow law. The results indicate faster strain rate in the feldspathic aggregate than in the quartz ribbons, which is consistent with strain localization in the feldspathic band (see modeling by Platt, 2015). We will further clarify this approach in the discussion and draw from the literature (e.g. Mehl and Hirth 2008; Warren and Hirth, 2006; Platt, 2015).

- page 2975, line 19: "recrystallized feldspars": the authors did not show evidence of recrystallized feldspar and in the conclusions?

  Yes, correct. We should not use "recrystallized feldspar" to be consistent with our interpretation. Neocrystallization of feldspars occurred by nucleation and growth from fractured fragments. We will modify the text accordingly.

- page 2976, line 4, 5: "(2) relatively dry conditions that inhibited crystal plasticity in feldspar." Why would dry conditions inhibit crystal plasticity? This is not discussed.

  True, we have not discussed this sufficiently. We referred to hydrolytic weakening, which has been typically investigated in quartz and olivine but not in feldspars. However, dislocation creep flow laws show that dry feldspar is remarkably stronger than its wet equivalent (e.g. Bürgmann and Dresen 2008 and refs therein). This will be mentioned and clarified in the revised manuscript.

Figures:
Scale bars are very hard to see in the Figures, please display them in a uniform size and font...

OK, figures modified.

Many thanks for your comments.
Yours sincerely,

Gustavo Viegas, Luca Menegon, Carlos Archanjo